Review of fiber optic methods for strain monitoring and non-destructive testing

Staas J.A. Bruinsma

TNO Institute of Applied Physics,
P.O. Box 155, 2600 AD Delft, the Netherlands

ABSTRACT

A number of fiber optic methods has been developed for the inspection of critical components of mechanical structures.
For inspection from a remote location various methods have been developed for the detection of cracks and strain. Some of these monitoring methods use a fiber mesh or OTDR techniques for distributed measurement of strain or to locate cracks.
Fiber optic methods for non-contact ultrasonic inspection require other techniques, e.g. a pulsed laser with fiber optic delay lines and velocity sensitive interferometers.

1. INTRODUCTION

Many modern structures, such as ships, bridges, aircraft and offshore structures have become very complex, in both their design and their use of exotic materials. Critical components of these structures require inspection on a regular basis.

The area to be inspected may be very difficult to access or may be situated in a hazardous environment. For these applications an automatic, real time and remotely operated system is required for detection of strain and cracks in these critical areas. The need for such a system for monitoring the structureal integrity has become even more significant, with the advent of new composite materials [1] and their integration into modern constructional design.
Various fiber optic monitoring methods have been developed for advanced materials [2] as well as for conventional materials. The methods are based on the detection of cracks, the measurement of strain and the detection of acoustic emission, arising from mechanical distortions and will be described in section 2, 3 and 4. The main reasons for the application of optical fiber technology in this area are:

- small dimensions and low weight
- intrinsic safety in an explosion hazardous environment
- non-electrical nature (galvanic separation)
- fibers can be guided to areas which are difficult to access
- fibers can be integrated into structures fabricated of composite materials
- fibers can be used for line sensors and distributed sensing to monitor extended paths (several km).

If the area to be inspected is accessible for test personnel and equipment, a number of non-destructive testing (NDT) methods to detect cracks can be applied. Many of these methods are based on ultrasonic pulse-echo detection. Non-contact ultrasonic inspection methods are preferred for inspection near corners and edges as well as inspection of objects at elevated temperatures or objects with a sensitive surface finish. Ultrasonic inspection using optical methods is a relatively new non-contact NDT technique. These systems are based on a combination of laser generation of ultrasound and interferometric detection of the resultant surface vibration. A few of these ultrasonic inspection systems have been developed using optical fiber technology. The optical fibers are used to control the beam characteristics of the generated ultrasound and to increase the flexibility of the inspection system. This ultrasonic inspection technique using optical fiber methods will be described in section 5 of this paper.

2. CRACK DETECTION

A very straightforward method may be used for the detection of cracks and areas experiencing excessive strain. A multimode optical fiber can be bonded to the surface, or integrated within the structural component. If a crack emerges in the structure the fiber will break causing an interruption of the transmitted beam. This break results in a number of optical phenomena which can be used for detection of the crack.

- The power coupled out of the end of the fiber will decrease drastically.
- At the location of the crack, an intense light spot will be visible, due to scattering of light at the fracture.
- Light will be reflected back from the fracture, enabling it to be located with an OTDR instrument.

If the adjacent crack in the structure closes, due to creep or unloading, the fiber fracture can still be detected in order to provide a record of damage or overstressing of the underlying material. Each of the above detection principles has its own limitations.
With a detection system based on measurement of attenuation, false alarms may arise from,

for example, any contamination of the fiber ends or change of coupling loss in connectors. A technique using visual inspection is clearly limited to those applications where the attached fiber is both visible and accessible. This does, however give a clear indication of the presence and location of the crack. The OTDR method, gives a clear indication of the presence and position of a crack and allows remote monitoring. However, a disadvantage is the expensive equipment needed, such as the OTDR instrument and a signal processing unit to locate and positively indentify the crack.

Several systems have been developed with a different design philosophy, for various applications and using different detection methods.

A system described by Hale and Johnson [3, 4] has been developed initially for offshore applications. Prefabricated sensors are used which consist of optical fibers on a tough glass composite tape. A rigid-modulus adhesive system is used to bond the backing tape to the component to be inspected. To maximize the sensitivity to underlying cracks, the optical fibers can be weakened and sensitized, so that the maximum strain that the fiber can withstand is reduced from a strain level of 5% to 1%. The system is available commercially [5]. The standard OptiCAT sensor (Fig. 1) has three parallel sensing optical fibers with a lateral spacing of 2 mm, so that the rate of crack length growth can be determined. Extension leads and alarm instrumentation (based on attenuation measurement) is supplied to enable monitoring from a remote location. Numerous tests have been carried out to assess the realiability of the system. According to the supplier, the sensors can reliably detect an increase of the crack width of 20 to 40 µm, for aircraft-type aluminium alloys and other metals, and 20 to 100 µm for brick and concrete. The performance of the sensor is unchanged by cyclic loading up to about 1000 microstrain (0.1%) in the temperature range -196°C to +120°C, in 100% relative humidity conditions or immersed in normal or sea water. The materials used for the sensors have been accepted as resistant to standard industrial and aviation fluids.

A somewhat different method has been developed at MBB Transport Aircraft division Bremen to monitor cracks and crack propagation in aricraft components [6]. This system, called "FORS", uses optical fibers of small diameter (20 to 100 µm) which can be etched to increase the sensitivity. These fibers are placed on perforated adhesive foil to facilitate attachment to the component. The fiber is in direct contact with the component as no intermediate layer is used. The foil is removed after curing of the adhesive. Alternatively, for applications at glass fiber reinforced plastic (GFRP) or carbon fiber reinforced plastic (CFRP) the fiber can be easily inserted in the laminate without disturbing the normal fabrication process (Fig. 2). This method is considered to be a reliable tool to detect delaminations, between various structural components. For these applications, bare single fiber or prefabricated tape with integrated bundles of fibers is used. The system has initially been developed for fatigue testing of aircraft components such as frames, stringers and rivet rows in the skin of wings. In monitoring mode, it is configured to automatically interrupt the fatigue test. The system has also been applied for the inspection of the steel rotor blades of a 2 MW wind turbine installation in Sweden, and for the inspection of a GFRP undercarriage structure of a new German train. Furthermore, a surveillance system has been developed for the centralized inspection of all critical components of the commercial jetliner "Airbus" during its life time. This Fiber Optic Nervous System "FONS" is designed for in-flight monitoring and will be accessible for flight and maintenance personnel.

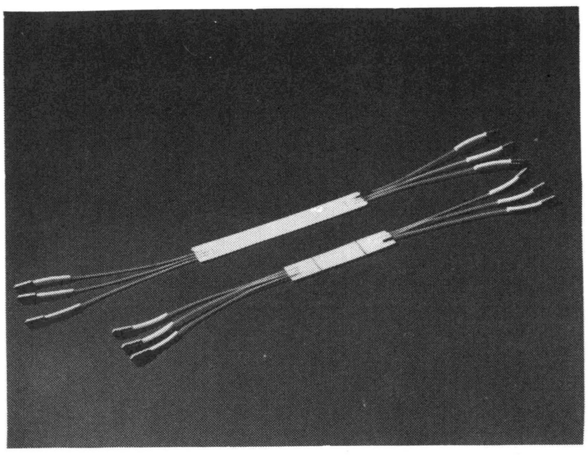

Figure 1. Crack monitoring sensors ("OptiCAT"), sensing length 1 inch and 2 inch

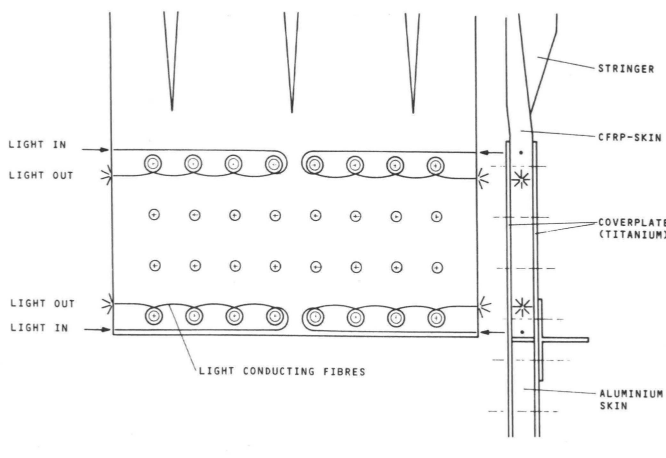

Figure 2. Optical fibers integrated in a critical component of an aircraft. Skin joint between inner wing (aluminium) and outer wing (carbon fiber reinforced plastic)

An optical fiber mesh has been tested for a damage assessment system for GFRP submarine sonar dome [7]. Two sets of orthogonally- oriented fibers are nested within the laminate during the fabrication process. When the fibers of the mesh are properly connected to LED's and detectors, the system can be configured to visualize the location of a damaged area (Fig. 3).

As an alternative, a video camera and image processing are applied to determine the position of the damaged area [8]. The fiber end faces at the detection side of the mesh are bundled and imaged onto the camera tube. Two images are subtracted, the initial image, before the occurrence of damage and the subsequent image. If fibers are broken, their location is highlighted as a result of this image subtraction.

3. STRAIN MEASUREMENT

The previous techniques determine, in an adequate way, the qualitative structural damage. More sophisticated techniques have been developed to interrogate structural behaviour by quantitative measurement of strain and strain distribution. For strain sensors, several operation principles can be used, including the modulation of transit time, transmitted intensity and phase or frequency modulation.

3.1. Modulation of transit time

The transit time of a circulating light pulse in a long (10-1000 m) multimode optical fiber is used to measure the absolute length of the fiber and its length variations [9]. A laser pulse passing through the fiber is detected and used to re-trigger a pulsed laser diode, so the system is operated as a time delay oscillator. Length variations are detected with a resolution of 0.2 mm. Other transit time detection schemes are based on a transit time resonator and on phase shift measurement [10]. Accuracy and stability of these methods are determined by the stability of the trigger system and transit time in the detector [11]. Commercial systems are available which are designed for measurement of the elongation of optical fibers in cables for telecommunication. A disadvantage of these methods is that only the integrated strain of the fiber can be determined.

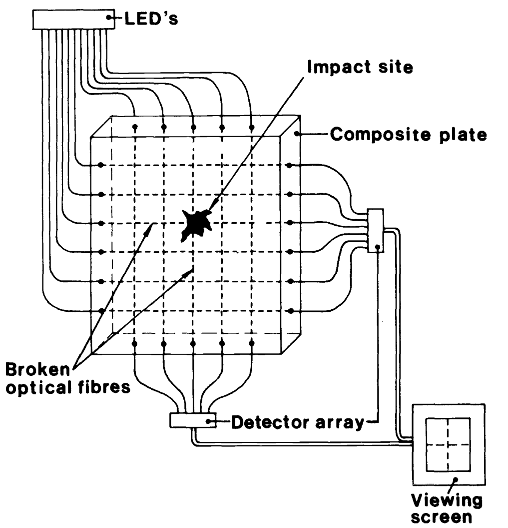

Figure 3. Schematic diagram of an optical fiber system showing the location of an impact damage in a composite structure

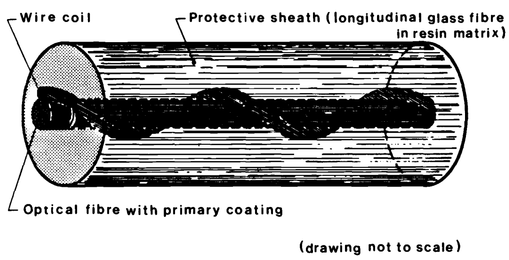

Figure 4. Optical fiber cable prepared to be sensitive to strain

3.2. Intensity modulation

A longitudinal strain can be converted into bending of an optical fiber, in order to cause a measurable increase of attenuation [12]. This can be achieved by bending the fiber in guiding the fiber along pins (pitch 20 mm), as well as by a metal helix (pitch 2.5 mm) around the fiber. In this way, the initial attenuation without strain is very low ($\ll 0.01$ dB/m). Low initial attenuation is needed to be able to inspect long structures. When the structure is strained, however, the fiber is bent sharply at the fixed positions, giving rise to a strong increase of attenuation (about 1 dB/m for 500 microstrain). An OTDR instrument and signal processor have been specially developed to measure strain distribution. With this instrument, a mean strain over a length of 0.25 m can be measured, with a resolution of 100 microstrain and a spatial resolution, along the fiber, of 0.25 m. The signal averaging time needed to achieve this resolution on a 100 meter fiber length is 1 minute. The strain not only changes the attenuation, but also modifies the modal

distribution in the fiber. As the sensitivity of the method depends on the modal distribution, this means that the sensitivity is modified at positions behind an area enduring a high strain level. Using an appropriate, empirically determined algorithm, the signal processing unit can correct for this. The OTDR instrument and signal processing unit has also been applied to detect deformations within a concrete beam, with a length of 4 m. For this purpose, fibers with a standard jacket have been installed in the beam during the casting process. The results of these experiments show a drastic change in attenuation, well before the occurrence of plastic deformation of the reinforcement steel.
A similar approach, using the same principle, is used in a special fiber cable manufactured by Felten & Gaulleaume Energietechnik AG, Köln [13]. A thin steel wire is spirally wound around a straight optical fiber. The pitch of the wire is much larger than the diamter of the optical fiber. In response to axial elongation the wire causes a periodic lateral displacement of the optical fiber, creating microbending. Mechanical protection is provided by a friction-locked sheath made of longitudinal glass fibers imbedded in a resin matrix (Fig. 4). This fiber cable can be supplied with instrumentation to measure the variation of attenuation integrated along the length of the fiber. Tests with this fiber cable show a fairly linear change of the attenuation as a function of the applied strain. This relationship is regarded to be reliable and was verified for repeated (about 1000 cycles) loading. The sensor fiber is proposed for a number of applications including strain monitoring of large steel and concrete structures and pressure vessels.

Bare optical fibers and polymer coated optical fibers without an intrinsinc mechanism to convert strain into attenuation have been imbedded between plies of graphite epoxy [14]. The attenuation due to the applied stress is measured with an OTDR instrument. Due to the regular surface roughness of the plies, the imbedded fiber is subjected to some microbending resulting in an initial loss of about 0.1 dB/m. The relatively high quiescent fiber attenuation limits the range of the OTDR system. This method may be used to qualitatively detect an area enduring excessive strain, but cannot be used for quantitative measurements.

3.3. Phase and frequency modulation

Interferometric techniques can be used to measure the line integral of strain over the length of a fiber bonded to, or imbedded in, a structure. The strain alters the physical length of the fiber and thus modulates the phase of light passing through the fiber. This phase modulation is detected with a fiber Mach-Zehnder or Michelson interferometer. Although some methods are proposed to measure strain using interferometric techniques, these methods are still mainly applied under laboratory conditions. The reasons for this may be firstly the limited need for such measurements and secondly the cost and complexity of many interferometric sensors. As the method is based upon measurement of a change in the optical path length of the fiber great care is required in the design of the instruments to eliminate errors produced by the high cross sensitivity of the fiber to temperature. Another problem related to interferometric strain measurement may be the limited dynamic range of interferometric sensors. White light interferometry can be applied to extend this range using an additional local receiving interferometer [15].

Interferometric strain sensors can be used for the detection of dynamic and static strain [16]. When heterodyne detection is applied, the measurement of an alternating strain reduces to a measurement of phase modulation, or frequency modulation (the well known Doppler shift), of the optical carrier frequency. For measurement of static strain, the phase change must be measured. Optical path length changes can also be measured using an interferometer with a differential path length and linearly modulating the frequency of the optical source [16]. In this wa y a beat frequency, proportional to the initial path length difference, is detected. Thus, measurement of the path length change is reduced to a measurement of a change in the beat frequency of the system. An added advantage using linear frequency modulation of the optical source is the ability to passively multiplex several strain sensors.

The two dimensional static stress field in a plate has been determined using an array of fibers [17]. This system has been demonstrated using six single-mode optical fiber interferometers. The sensing fibers are attached to the plate in a configuration somewhat similar to the diagram in Fig. 3, using two orthogonal sets of three fibers. Examination of each individual fiber for the same deformation of the plate yielded a two-dimensional matrix of the static strain in the plate.

Axial strain can also be measured with a few-mode optical fiber, using mode-mode interference [18]. Such single-fiber interferometric schemes may provide a high common-mode rejection capacity as the two arms of the interferometer have a similar environment. Furthermore the strain sensitivity has been reduced compared to normal dual path interferometers.

4. ACOUSTIC EMISSION DETECTION

The potential importance of acoustic emission detection and analysis for the inspection of composite structures has been well established. Time and frequency domain analysis of acoustic emission events yields information about the type, geometry and location of defects, as well as how material failure may occur. A defect arising in, for instance, a fiber-reinforced plastic component will generate acoustic stress waves in the structure. The sensor usually used to detect these acoustic waves is the piezo-electric transducer. As in the case of hydrophones, optical fibers present an attractive means for the detection of acoustic waves. Furthermore, when required to measure the acoustic emission of composite materials, the fiber has the advantage that it can easily be imbedded in the structural component.

A Mach-Zehnder interferometer, with one of the single mode fiber arms attached to a graphite-epoxy composite, is used by Wade [19]. The detected signals correlated well with piezo-electrically-detected acoustic emission events.

Experiments have also been carried out using a few-mode optical fiber and mode-mode interference [20]. For these experiments, a Helium-Neon 633 nm optical source and an optical fiber with a cutoff wavelength at 850 nm have been used. If the fiber is mechanically perturbed, the individual mode contributions to the far field intensity function change, the speckle pattern shifts and the detected signal varies. This system has the advantage of being simple and inexpensive. It has been shown that the sensitivity and frequency response of this method allow discrimination between acoustic events generated by graphite fiber breakage and by internal matrix cracking, by analysis of risetime and duration of the detected event.

Two other methods which may be used for the detection of acoustic emission are based on polarization and intensity modulation [21]. The fiber is pressed against the surface of the material to be tested, ultrasonic waves will thus modulate the transverse stress in the fiber. In the first case, birefringence produced by the transverse stress in a single-mode fiber generates a change of the state of polarization, which is converted into an intensity modulation. The second approach uses a fiber whose cladding has a higher compressibility than the core, such as a Plastic Clad Silica (PCS) fiber. Under compression, the numerical aperture of the fiber reduces with a subsequent reduction in optical transmission. Both methods have been used to detect 1 MHz ultrasound stress waves in materials.

5. NON-CONTACT ULTRASONIC INSPECTION OF FLAWS

A combination of (fiber optic coupled) laser generation of ultrasound and an (optical fiber) interferometer for the detection of the resultant surface displacement leads to a technique which is very useful for a wide variety of ultrasonic inspection tasks, including those in areas which are difficult to access, inspection of objects at high temperatures, as well as more routine inspection and quality control in industrial environments. Such a system is to be applied for the measurement of thickness, velocity, grain size and the detection of flaws. The development of these methods is still more or less at a laboratory stage, the aim is to increase both the efficiency of the laser generation process as well as the sensitivity of optical detection methods, especially for detection at optically diffusing surfaces.

5.1. Laser generation of ultrasound

For generation of ultrasonic pulses without distortion of the object surface the following mechanism is used. A laser pulse incident on a surface will be partly absorbed by the material and will thus generate a sudden rise in temperature of a surface layer of the material. This thermal shock causes expansion of a small volume at the surface of the object which generates thermo-elastic strains [22]. This method has been used for some applications using bulk optical systems and single optical fibers for delivery of the laser pulse energy. The directivity of such a thermo-elastic source is completely different from other well-known sources, and is regarded as a serious handicap in the application of laser generation. To control the beamwidth and beam direction of the optically-generated ultrasonic waves a fiber phased array has been developed [23]. In this way the generated ultrasonic beam can be focussed and directed to a particular inspection point below the surface of an object, Fig. 5. This system has been optimized for the detection of fatigue cracks at rivet holes in aircraft structures in a pulse-echo mode of operation. For continuous wave generation of ultrasound other optical array techniques are proposed using an acousto-optic modulator to harmonically modulate a Q-switched laser to produce a gated sine wave several cycles long [24]. This method has not yet been experimentally verified.

5.2. Optical detection of ultrasound

Several optical methods have been developed for the detection of ultrasound [25]. The application of optical fibers for these methods increase the flexibility of an instrument and enable scanned inspection. Some optical fiber systems are based on a normal Michelson or Mach-Zehnder interferometer. These systems have been used in the laboratory for various applications, such as the measurement of the acoustic wave amplitude of a SAW transducer [26]. Semiautomatic scanning measurements have been made of the vibration amplitude distribution of various piezo-electric-ceramic elements [27]. For these measurements a sensing system has been applied which can be used to measure the out-of-plane as well as the in-plane component of the surface vibration.

With the above systems, surface displacement is detected with a uniform frequency response. In this way, these systems are very sensitive to ambient low-frequency noise. An interferometer which is sensitive to surface velocity instead of displacement ensures excellent immunity to ambient vibrations. The sensitivity of such a velocity interferometer is proportional to the acoustic wave frequency. Several somewhat similar systems based on a time delay interferometer are proposed, see Fig. 6. Added advantages of this approach are firstly that the interferometer part of the detector can be constructed in a compact and robust form and secondly that the fiber lead to the object does not form part of the interferometer, which means that its length is not critical. The first system (Fig. 6a) can be used to detect continuous wave surface vibration. The other system (Fig. 6b) can be used in homodyne detection mode for transient (pulsed) ultrasonic signals. They have been applied to the characterization of surface defects using continuous wave excitation [28], for detection of sub-surface defects at rivet holes in aircraft structures using the ultrasonic pulse-echo mode of operation [29] and for measurement of the wall thickness of hot (1230°C) pipes on a production line [30]. The latter system however uses bulk-optics for the laser generation system and for the time delay interferometer, which has a free space length difference of 3.7 meter.

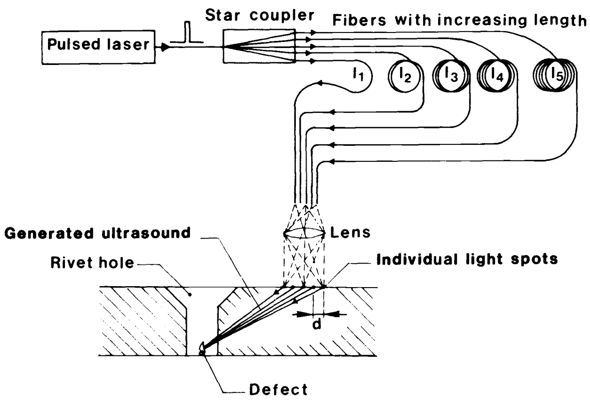

Figure 5. Set-up for beam steering of laser-generated ultrasound using an optical fiber phased array

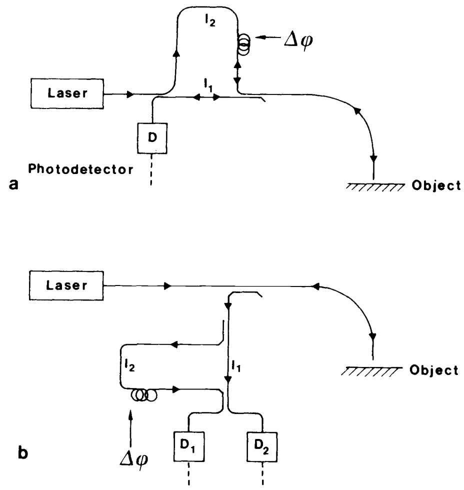

Figure 6. Schematic diagrams of two time delay interferometers for the detection of ultrasound

6. CONCLUSIONS AND DISCUSSION

A number of fiber optic methods based on different operating principles and designs have been developed for monitoring and active inspection applications. Many of these methods meet the required performance for specific applications. As many different special purpose systems are needed to cover the applications, the market for the individual devices will be relatively small. In many cases the development cost for a reliable sensor system, after the research stage, is large in relation to the aimed market area. As a result it is expected that these sensors will only gradually be introduced, partly as a spin-off of larger sensor development programs.

Optical fiber methods do add interesting new possibilities to the already existing methods for monitoring structural integrity and as a consequence the number of practical applications within this area will grow gradually. Undoubtedly these methods have many advantages over conventional systems. However, the introduction of some of these sensor systems is somewhat slackened by the lack of practical experience with these novel methods. Various crack monitoring sensors and a system for measuring strain have already been introduced as practical engineering devices. Furthermore it can be expected that especially imbedded sensors, for detection of the acoustic emission arising from mechanical distortions, will be applied in the near future for monitoring of critical components of aircraft and aerospace structures.

Several inspection tasks can be facilitated by applying opto-acoustic NDT methods using optical generation and detection of ultrasound. Opto-acoustic NDT systems will especially be applied for inspection of hot objects and for the inspection of coatings. The cost of an individual device will remain relatively high, as the market area for these systems is small.

7. REFERENCES

1. Summerscales J., Embedded optical sensors in fibre reinforced plastics, International Journal of Optic Sensors, Vol. 1, No. 4, 1986, pp. 287-299.
2. Ehrenfeuchter P.A. and Claus R.O., Optical fiber waveguide methods for advanced materials, Proc. International Metallographic Society Meeting, Monterey, CA, July 1987.
3. Hale K.F., Optical fibre sensors inspection monitoring, Phys. Technol. Vol. 15, 1984, pp. 129-135.
4. Johnson R.F., Optical fibres and their application to the measurement of strain and displacement and for the detection of cracks, Proc. Test & Transducer Conference, Wembley England, October 1986.
5. "OptiCAT crack monitoring sensor, OptiCAT is a registered trade mark of Ceemaid Division, British Maritime Technology Ltd., St. John's Street, Hyte, Southampton, Hants SO4 6YS, UK.
6. Hofer B., Fibre optic damage detection in composite structures, Proceedings of the 15th September 1986, pp. 135-143.
7. Crane R,M., Macander A.B., Taylor D.W. and Gagorik J., Fiber optics for a damage assessment system for fiber reinforced plastic composite structures, Rev. of Progress in Quantitative NDE, Vol. 2B, Plenum Press, New York 1983, San Diego, August 1982, pp. 1419-1430.
8. Jen C.K., Farnell G.W., Parker M. and Cielo P., A fibre optic damage monitor, Rev. of Progress in Quantitative NDE, Vol. 4B, Plenum Publishing Corporation, New York, 1985, pp. 831-838.
9. Johnson M. and Ulrich R., Fibre optical strain gauge, Electr. Lett., 14, 1978, pp. 432-433.
10. Brininstool M.R., Measuring longitudinal strain in optical fibers, Opt. Eng., Vol. 26, No. 11, 1987, pp.1112-1119.
11. Mamon. G., Youmans D.G., Sztankay Z.G. and Mongan C.E., Pulsed GaAs laser terrain profiler, Applied Optics, Vol. 17, No. 6, 1978, pp. 868-887.
12. Bruinsma A.J.A., Van Zuylen P., Lamberts C.W. and de Krijger A.J.T., Fibre optic strain measurement for structural integrity monitoring, Proc. 2nd Int. Conf. on Optical Fibre Sensors, OFS'84, Stuttgart, September 1984, pp. 399-402.
13. Federmann H., Levacher G., Noack G. and Beck M., Development of processes for quality control and monitoring of critical components made of fibre composite materials using optical fibre, Faserverbundwerkstoffe, Band 2, Springer Verlag Heidelberg-New York-Tokyo, June 1985, pp. 223-262.
14. Claus R.O., Jackson B.S. and Bennet K.D., Non-destructive testing of composite materials by OTDR in imbedded optical fibers, proc. SPIE Int. Symp., San Diego, Vol. 566, 1985.
15. Bosselman T. and Ulrich R., High-accuracy position-sensing with fiber-coupled white-light interferometers, Proc. 2nd conf. on Optical Fibre Sensors, OFS'84, Stuttgart, September 1984, pp. 361-364.
16. Uttam D., Culshaw B., Ward J.D. and Carter D., Interferometric optical fibre strain measurement, J. Phys. E: Sci. Instrum., Vol. 18, 1985, pp. 290-294.
17. Wade J.C. and Claus R.O., Interferometric techniques using embedded optical fibers for the quantitative NDE of composites, Rev. in Progress in Quantitative Non-destructive Evaluation, Plenum Press New York 1983, San Diego, CA, August 1982, pp. 1731-1739.
18. Shankaranarayanan N.K., Srinivas K.T. and Claus R.O., Mode-mode interference effects in axially strained few-mode optical fibers, Proc. SPIE, Vol. 838, San Diego, CA, August 1987, paper 57.
19. Wade J.C., Zerwekh P.S. and Claus R.O., Detection of acoustic emission in composites by optical fibre interferometry, Proc. IEEE Ultrasonics symposium, 1981, pp. 849-853.
20. Bennett K.D. and Claus R.O., Internal monitoring of acoustic emission in graphite-epoxy composites using imbedded optical fiber sensors, Proc., Rev. of Progress in Quantitative NDE, Conf. San Diego, CA, August 1986.
21. Cielo P. and Lapierre J., Fiber-optic ultrasound sensing for the evaluation of materials, Applied Optics, Vol. 21, No. 4, 1982, pp. 572-576.
22. Scruby C.B., Dewhurst R.J., Hutchins D.A. and Palmer S.B., Laser generation of ultrasound in metals, from: Research Techniques in Non-destructive Testing, Vol. 5, ed. R.S. Sharpe, Academic Press, 1982.
23. Vogel J.A., Bruinsma A.J.A. and Berkhout A.J., Beamsteering of laser generated ultrasound, Proc. Conf., Ultrasonics International 87, London, July 1987.
24. Addison Jr. R.V., Graham L.J., Linebarger R.S. and Tittmann B.R., Systhesis of an ultrasonic array using laser-based techniques, Proc. IEEE, Ultrasonics symposium, 1987, pp. 1109-1113.
25. Monchalin J.P., Optical detection of ultrasound, IEEE Trans. on Ultrason., Ferro-electr. and Freq. Contr., Vol. UFFC-33, No. 5, September 1986, pp. 485-499.
26. Jungerman R.L., Bowers J.E., Green J.B. and Kino G.S., Fiber optic laser probe for acoustic wave measurements, Appl. Phys. Lett., Vol. 40, No. 4, 1982, pp. 313-315.
27. Hirose Y, Abe T., Komai H. and Tsuzuki Y., Optical fibre vibration sensing system, The Transactions of the IEICE, Vol. E 70, No. 3, March 1987, pp. 195-202.

28. Jungerman R.L., Khuri-Yakub B.T. and Kino G.S., Optical detection of acoustic displacements for the characterization of surface defects, Materials Evaluation, Vol. 42, April 1984, pp. 444-450.
29. Bruinsma A.J.A., Non-contact detection of pulsed acoustic displacements for the evaluation of sub-surface defects, 4th Int. Symp. on Optical and Opto-electronic Applied Science and Engineering, The Hague, April 1987, SPIE Proc., Vol. 798, 1987.
30. Keck R., Krüger B., Coen G. and Häsing W., Wanddickenmessung an 1230°C heissen Rohrluppen, Stahl und Eisen, Vol. 22, 1987, pp. 1028-1031.